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Flood Potential: A New Method for Quantifying and Communicating the Magnitude and Spatial Variability of Floods

Enhanced understanding of flood hazards (Figure 1; Figure 3) and how they vary across regions and continents is needed to help protect lives, infrastructure, and property; such understanding is necessary to develop more resilient stream valley communities. Using the greater Southern Rocky Mountains region as a study area, a novel methodology was developed to predict, rank, and communicate expected flood magnitudes across similar responding areas (zones). For an initial study area (Figure 4), up to 93% of the variance was explained by regression models of record peak discharges at long-term streamgages for 11 derived zones, in three Forest Service regions.

These regressions define the ***expected flood potential*** of each zone, a term introduced to assist practitioners, policy makers, and the public in understanding what flood magnitudes can be expected given the maximum recorded streamgage floods in similar-responding watersheds. Indices were also developed for comparing flood hazards across wide geographic areas.

Preliminary analyses indicate that the method is valid in other regions, including New England, Southern Midwest, Gulf Coast, and West

Figure 1: Flood damage in Glen Haven, Colorado (10/18/2013).

StreamNotes is an aquatic and riparian systems publication with the objective of facilitating knowledge transfer from research & development and field-based success stories to on-the-ground application, through technical articles, case studies, and news articles. Stream related topics include hydrology, fluvial geomorphology, aquatic biology, riparian plant ecology, and climatology.

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Coast regions of the continental United States, as well as in Puerto Rico.

Key questions that this new methodology helps to answer include:

- Given the record of floods within a derived area, what flood magnitudes can be expected for a specific watershed?
- What observed floods are most accurately referred to as extreme, and what floods are the most extreme?
- How do expected flood magnitudes, flashiness, and overall hazard in a given area compare to other areas?

Information and data regarding the Flood Potential method are available here.

Key references for additional information on the method development include Yochum (2019) and Yochum et al. (2019).

Methodology

Based primarily on streamgage records across the greater Southern Rocky Mountains region, and supplemented by paleoflood data, this work developed a new method for understanding flood hazards.

The method utilizes the maximum record discharge at longer-term streamgages across zones of similar flood potential. Regressions of the maximum experienced discharges as a function of drainage area (and, in some areas, an additional explanatory variable) were fit for each zone to provide a tool that can be used to quantify flood potentials. Additional analyses to quantify flood seasonality and identify trends were performed using the largest 5% floods. Hence, this method uses a space-for-time substitution that leverages data collected in neighboring watersheds to understand expected flood magnitudes in a watershed of interest.

An example plot illustrating the findings for a zone that consists of the core high-elevation portion of the Southern Rocky Mountains is provided in Figure 2. The dark gray line is the regression fit for the record peak discharges; this line is the ***expected flood potential***, with the upper 90% prediction limit (light gray line) being the ***maximum likely flood potential***. Floods greater than the maximum likely flood potential are considered extreme, with the departure above this line indicating the level of extremity. The expected flood potential can easily be computed for any location (within the derived watershed area ranges), to quantify expected flood magnitudes using a method independent of flood-frequency analyses (i.e., independent of analyses that define the 100-year flood), for infrastructure design and other stream-valley management activities that are concerned with large floods.

To compare how floods vary between zones, a few indices were developed:

- ***P_f* = Flood Potential Index**: Compares flood magnitudes to a low flood potential zone (2), and facilitates comparisons between any zones.
- ***V_f* = Flood Variability Index**: Describes within-zone flood magnitude variability, with higher values indicating greater variability.
- **F = Beard Flash Flood Index**: quantifies flashiness, with higher values indicating greater difference between the magnitude of large floods and more typical annual floods.
- ***H_f* = Flood Hazard Index**: provides a summary of overall hazard, accounting for both flood magnitude and flashiness.

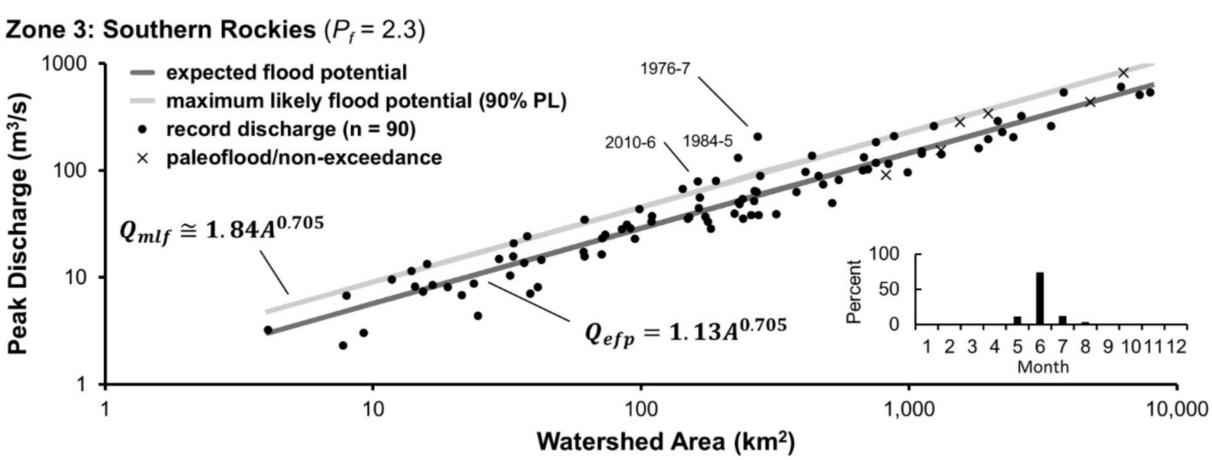

Figure 2: Expected flood potential plot for zone 3, the Southern Rockies. The black dots indicate the record peak discharges for each streamgage in the zone, which were used to develop the expected flood potential regression (dark gray, R^2 = 0.92) and the maximum likely flood potential (light gray, 90% prediction limit). Available paleoflood data are also plotted (marked with "x").

- E_f, = **Flood Extreme Index**: ranks flood magnitudes and extremity, with higher values indicating larger or more extreme events, and values less than 1 indicating a flood is less than the expected flood potential.

Readers are referred to Yochum et al. (2019) for additional information on the methodology.

Key Results

New methodologies were developed for predicting flood magnitudes at ungaged locations, identifying and ranking extreme floods in a systematic way, and comparing widely varying flood potential across continental-scale areas. Strategic yet simple language for communicating expected flood hazards are introduced to help practitioners, citizens, and policy makers understand risk.

The developed method assists with answering such questions as:

- **What large flood magnitudes can be expected at a given ungaged location?** This information is needed for such applications as designing stream valley infrastructure.
- **Is a specific streamgage analysis biased?** The method utilizes streamgage information using an independent approach to flood-frequency analyses; hence, this method can provide an assessment of bias in statistical fits. For example, logPearson analyses of short streamgage records can be biased high due the presence of an unusually large flood in the record, while a long streamgage record that lacks a large flood that other zonal watersheds indicate is likely results in a low bias in flood magnitudes. Both of these scenarios can be detected using the Flood Potential method.

Figure 3: Flood impacts in Jamestown, Colorado (10/29/2013).

- **How reasonable are the results of regional flood frequency regression equations?** Many practitioners often have poor confidence in the results of regional regression analyses, which are used for predicting flood frequency at ungaged locations; this method can verify or raise concerns regarding the results of such analyses.
- **What areas are inherently prone to larger or smaller floods?** The Flood Potential Index is used to understand how flood sizes vary by zones, across regions and continents. Such understanding is valuable for more informed decisions regarding the erosion hazards of stream corridors (fluvial hazard zones), the stability of stream restoration projects, and the inherent risks of wildfire-induced flooding on communities.
- **Is a specific flood extreme, or rather a typical large flood?** Many floods are described as extreme when, in fact, they are instead typical in magnitude, compared to events recorded in neighboring watersheds (and should be expected). Overly sensational language is counterproductive for encouraging communities to develop resilience for when the next expected large flood magnitude occurs.
- **Compared to other floods in the area, how extreme is a flood?** Greater insight into the mechanisms that induce the most extreme floods can help increase the understanding of driving mechanisms, and help us prepare for the possibility of shifts in flooding due to global warming.

Use of Indices

Results for the initial analysis extent are shown in Figure 4 and Figure 5. The plan view map of Figure 4 shows the derived zones for the initial study area. The colors indicate varying experienced flood magnitudes, with the warmer colors denoting high flood potential and the cooler colors low flood potential. These differing flood potentials are quantified using the flood potential index (P_f), which ranged from 1.0 (zone 2) to 15 (zone 1S) for the analysis extent. This means that, for a given watershed area, floods in zone 1S experience floods that are, on average for a given watershed area, more than 15 times larger in magnitude than the adjacent zone 2. For the Southern Rocky Mountains zone (3; Figure 2), P_f = 2.3; floods in this zone, on average, are 2.3 times the magnitude of those in zone 2 while floods in

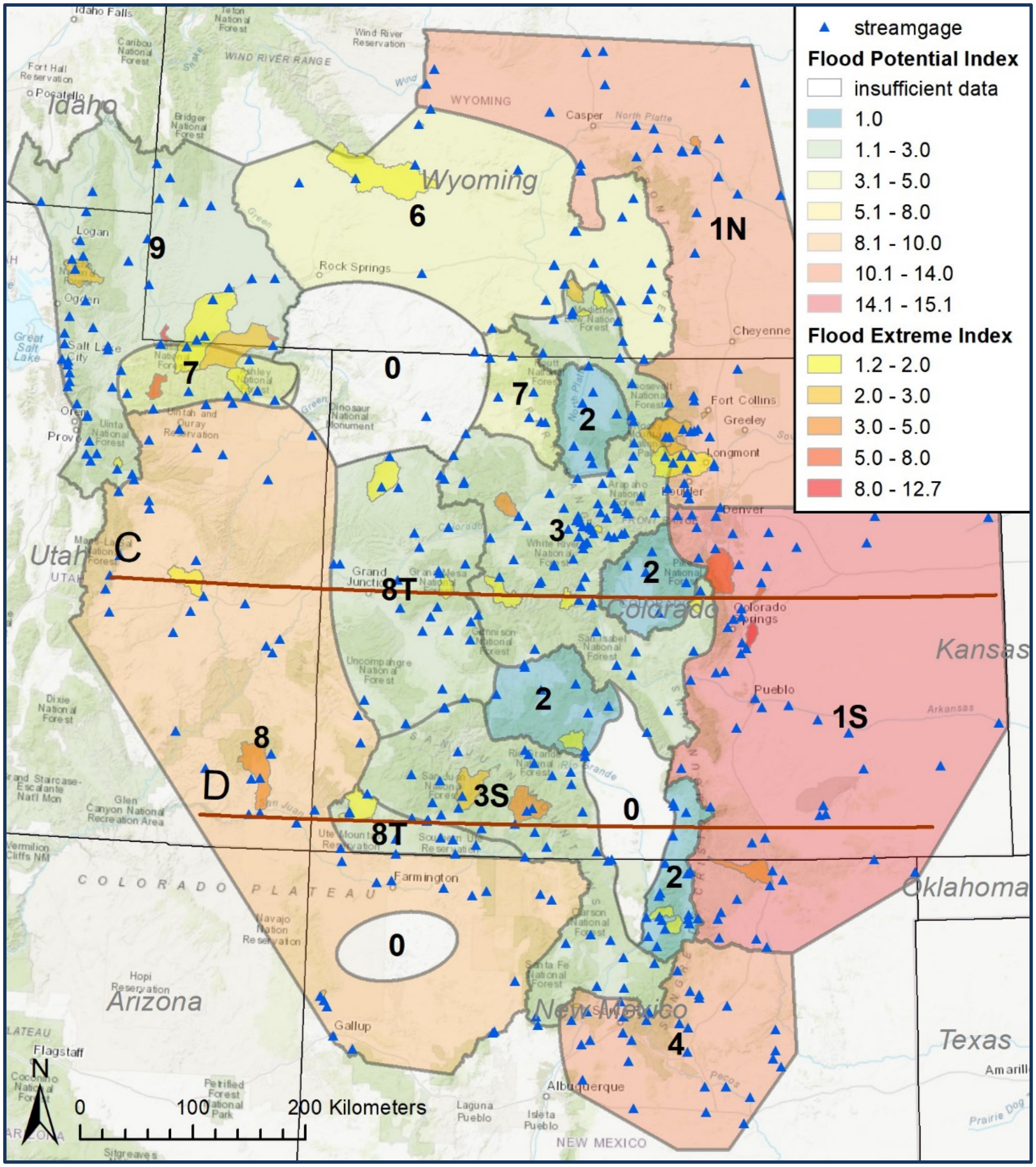

Figure 4: Initial analysis extent and results for the Flood Potential methodology for predicting, ranking, and communicating flood hazards. Analyses of long term streamgage data are performed across zones of similar flood responses. The warmer colors of the zone polygons (labeled 1S to 9) indicate higher expected flood potential (the label 0 refers to areas with insufficient streamgage data). Watersheds that have experienced extreme floods, as defined using the developed methodology, are also shown (with the warmest colors indicating the largest flood extreme index values). Cross sections lines are also provided (see Figure 5).

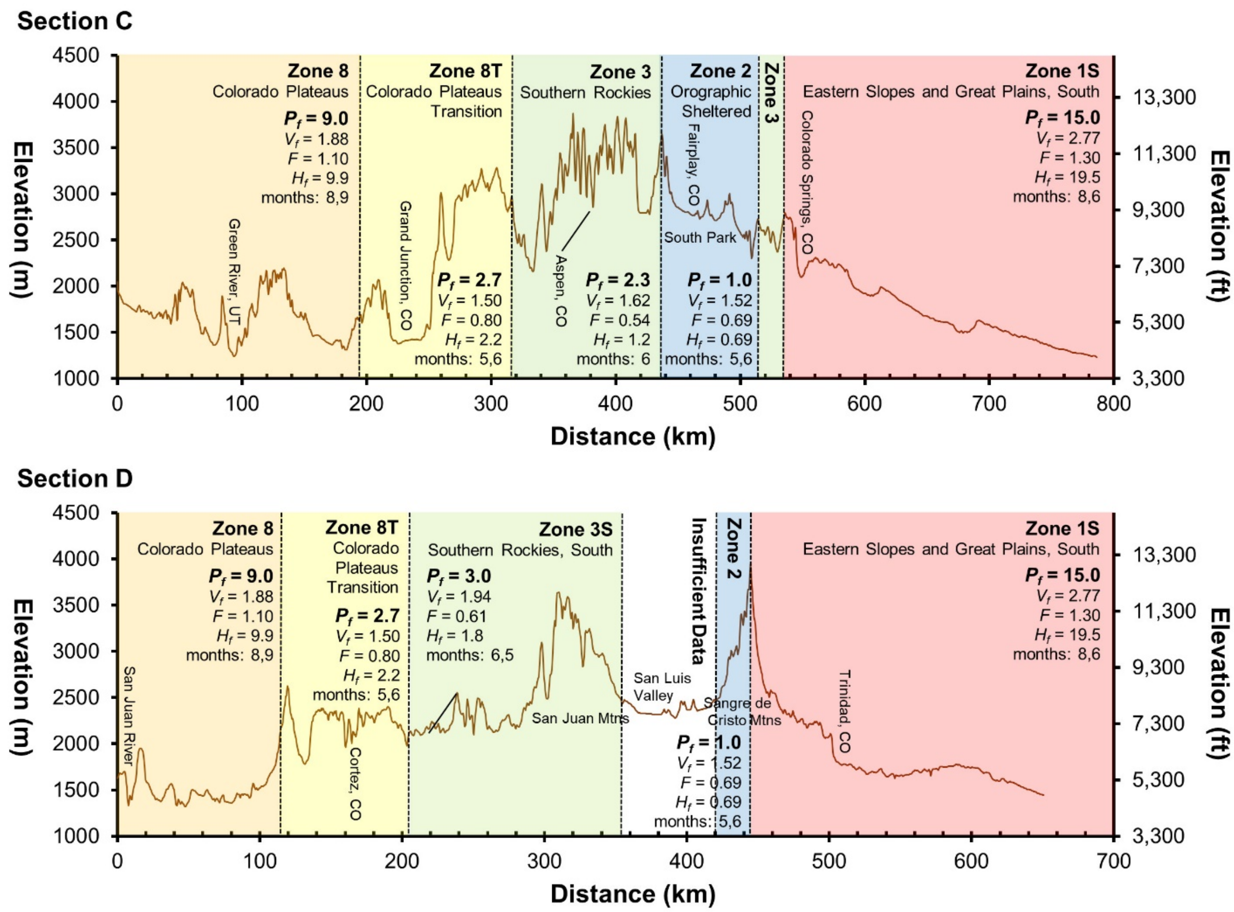

Figure 5: Flood potential results illustrated using cross sections across the greater Southern Rocky Mountains region. Warmer colors indicate higher flood potential, while cooler colors indicate lower flood potential.

zone 1S are 15/2.3 = 6.5 times larger than in zone 3. Hence, use of the indices allows simple comparison of expected flood magnitudes between any zones.

Zone 1S, as well as neighboring zones 1N and 4, consist of the High Plains and adjacent foothills of the Southern Rocky Mountains. These areas are primarily semiarid, but periodically experience large floods due to large-scale weather patterns. For example, 1965 flooding was associated with an intense cutoff western low that steered warm, moist, unstable air from the Gulf of Mexico into eastern Colorado and a blocking pattern forced a cold front to be stationary for three days, inducing extreme rains (Schwarz, 1967; Hirschboeck, 1987). The 2013 Colorado Front Range floods drew moisture from the Gulf of Mexico, Caribbean Sea, and tropical eastern Pacific Ocean (Gochis et al., 2015) – despite prevailing winds being from the west, moisture for the largest floods is drawn at least in part at lower levels from the Gulf of Mexico. Floods in these zones also tend to be flashy, with a flash flood index (F) of 1.3.

In contrast, zone 2 consists of large mountain-surrounded high-elevation valleys that are orographic sheltered from large flood producing mechanisms (intense rainfall, rapid snowmelt), and experience floods that are less flashy ($F = 0.69$). The regional-scale cross sections of Figure 5 illustrate how flood potential varies by elevation and topographic sheltering, with higher flood potentials and flashiness being to the east, south, and west of the Southern Rocky Mountains while the mountains themselves are sheltered from large floods.

Hence, due to differing dominant meteorological and hydrological processes, each zone varies in its flood potential. Zones with higher flood potential are prone to higher flood peaks and greater erosion hazards, with higher flashiness additionally associated with floods that are more unexpected. Infrastructure such as culverts and bridges in areas with higher flood potential need to be sized larger, and roadway embankments along streams in these areas are more prone to washouts. Conversely, in areas with low flood potential, hazards are much less since experienced floods are not only relatively small in magnitude but can also be not as flashy and unexpected (such as in zone 2).

Such knowledge can be leveraged to develop understanding on where wildfire areas may experience the greatest (or least) floods (to maximize efficiency in the Burn Area Emergency Response program) and where transportation infrastructure is most at risk from fluvial hazards from the large floods that will inevitably occur. Understanding of where floods tend to be larger and more flashy can also be very relevant for planning stream restoration activities; expending limited project funding in areas with higher flood potential is inherently riskier than projects in low flood potential areas.

Flood Potential Discharge Predictions

The equations in Figure 2 (and the companion plots of Figures 3 to 5 in Yochum et al., 2019) can be used to predict expected large flood magnitudes at most ungaged locations, for use for a variety of purposes including the design of infrastructure. These equations predict expected flood magnitudes based on watershed area and, in places, additional watershed characteristics (such as average elevation or annual precipitation). Additionally, the months of occurrence of the 5% largest floods that are also provided in these plots help foster understanding of when the largest floods will most likely occur within each zone.

Extreme Floods

The method provides a systematic approach for quantifying and ranking extreme floods. Figure 4 highlights watersheds that have experienced extreme floods, with warmer colors indicating more extreme magnitudes. The most extreme floods within this analysis extent occurred in zone 1S during May, 1935 and June, 1965. Instead of the common situation where large flood events (such as the 2013 Colorado Front Range Flood) are referred to as being extreme in magnitudes across the entire impacted extent, this method allows us to specify which specific watersheds (where peak flows have been computed) experienced extreme floods and how extreme the flooding was compared to past events.

For the 2013 flood, the Little Thompson and St. Vrain watersheds experienced extreme floods, but these floods were less extreme than The Big Thompson flood of 1976 and the Spring Creek (Fort Collins) flood of 1997. Other areas that experienced large floods and were impacted by large amounts of geomorphic adjustment and damages to infrastructure, businesses, and homes (such as in Glen Haven, Figure 1) experienced flood magnitudes that were greater than the expected flood potential but still less than the maximum likely flood potential. This method can help mitigate inappropriate sensationalism and develop realistic expectations on the size of floods to expect in the future.

Management Implications

- A novel methodology was developed to predict, rank, and communicate expected flood magnitudes across zones of similar watersheds.
- The term ***expected flood potential*** was introduced to describe expected flood magnitudes from regressions of maximum recorded discharges at long term streamgages.
- The ***maximum likely flood potential*** is defined using the 90% prediction limit, with floods greater than this considered extreme. Hence, this approach provides a consistent method for identifying extreme floods.
- This methodology can be used for computing flood discharges for infrastructure design, including culverts and bridges.
- Indices were developed to allow practitioners to: compare expected flood magnitudes between zones; understand within-zone flood variability; quantify flood flashiness; quantify overall flood hazard, considering both magnitudes and flashiness; and rank extremes.

Example Applications

Two examples are provided to illustrate the use of the method for developing flood magnitude predictions, and comparing these results to flood frequency analysis results. Computations are provided, to provide clarity for practitioners. These examples are for a stream that does not have streamgage data at the point of interest (Cache la Poudre River, drainage area = A = 478 mi^2) and one that does (Buckhorn Creek, A = 136 mi^2).

The first example is for the **Cache la Poudre River** in Poudre Park, Colorado, a community within the Roosevelt National Forest. This river's watershed (Figure 6) is in two zones, with the upper watershed being in the Southern Rocky Mountains (zone 3, P_f = 2.3) while the lower watershed is in the Eastern Slopes and Great Plains (zone 1N, P_f = 13.8), a zone that experiences floods that are 13.8/2.3 = 6 times larger than the upper portion of the watershed. The expected flood magnitudes are computed by weighing the portions of the watersheds that are in zone 3 and zone 1N. The equations provided in Figure 3 of Yochum et al. (2019) are used to compute both the expected flood potential (Q_{efp}) and the maximum likely flood potential (Q_{mlf}) discharges. Specifically, the watershed is composed of 965 km^2

of zone 3 and 272 km^2 of zone 1N (overall watershed area = 1237 km^2 = 478 mi^2). Computations in zone 3 are performed using both watershed area and average annual precipitation (P = 681 mm; Daly et al. 2008), while zone 1N is computed using only watershed area (A). Specifically:

$$Q_{efp} = 0.0392A_3^{0.723}P^{0.492} + 31.9A_{1N}^{0.384}$$

$$\begin{aligned} Q_{efp} = {} & 0.0392(965)^{0.723}(681)^{0.492} \\ & + 31.9(272)^{0.384} \\ & = 139.6\ cms \\ & + 274.6\ cms \\ & = 414.2\ cms \end{aligned}$$

$$Q_{mlf} = 0.0656A_3^{0.723}P^{0.481} + 56.1A_{1N}^{0.382}$$

$$\begin{aligned} Q_{mlf} = {} & 0.0656(965)^{0.723}(681)^{0.481} \\ & + 56.1(272)^{0.382} \\ & = 217.5\ cms \\ & + 477.5\ cms \\ & = 694.99\ cms \end{aligned}$$

Hence, given the record of zonal streamgages, a space-for-time substitution indicates that a flood with a magnitude of 410 cms (14,600 cfs) can be expected on the Cache la Poudre River at Poudre Park, and that a flood of 690 cms (24,500 cfs) is the maximum likely flood magnitude. A flood greater than this latter magnitude, should it occur, would be extreme.

These results compares to a 100-year flood peak of 170 cms (6100 cfs). This value was computed using the results of regional regressions of logPearson streamgage analyses, using USGS StreamStats (Capesius and Stephens, 2009; Kohn et al. 2016). The larger values predicted by the expected flood potential method is due to the influence of eastern portion of the watershed, which local streamgages indicate as having the potential for producing large floods. The regional regression results may be under predicting the actual flood potential for this site.

Buckhorn Creek is a much smaller stream with an adjacent, lower-elevation watershed to the Cache la Poudre (Figure 6). This watershed is located entirely in zone 1N. The streamgage record indicates bimodal flood peaks, with most of the 30 year record recording annual peak flows less than 28 cms (1000 cfs), while also recording 4 floods greater than 280 cms (10,000 cfs). The largest recorded discharge (that was not associated with a dam failure) is 320 cms (11,200 cfs; 9/12/2013). A logPearson analysis of the streamgage records (England et al., 2018) indicates a 100-year flow estimate of 590 cms (20,900 cfs) using the station skew and excluding a dam failure influenced peak. Use of a regional skew adjustment would increase the estimate.

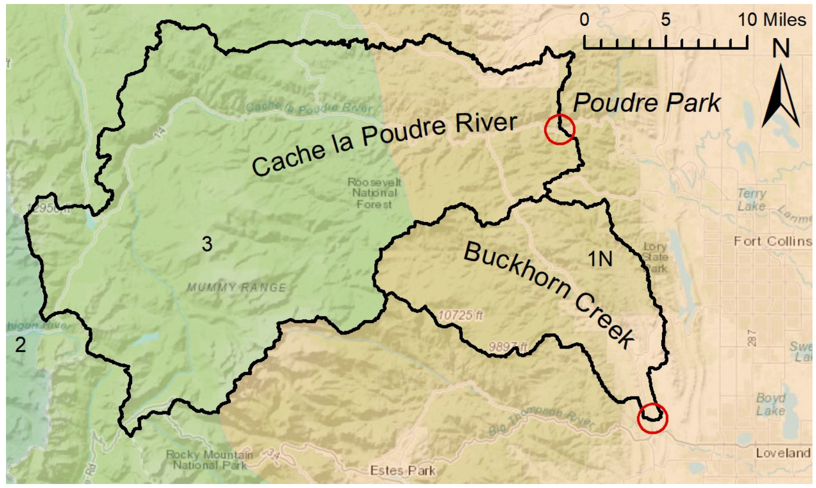

Figure 6: Watershed delineations for the Flood Potential examples, with the coloring indicating the flood potential index variability for zones 1N, 3, and 2. The red circles indicate the computation points.

In contrast, the expected flood potential was computed to be 300 cms (10,700 cfs) for Buckhorn Creek, with a maximum likely flood potential of 530 cms (18,600 cfs) – the bimodal flood distribution is biasing the streamgage flood frequency analysis, resulting in overestimated flood magnitudes. The flood potential method illuminates this issue and provides alternative estimates for the expected magnitude of large floods. It also indicates that the 2013 peak discharge should not be categorized as extreme in magnitude in this watershed, which is reasonable since three other similar-magnitude floods have also been recorded.

Additionally, the streamgage records indicate that while the upper Cache la Poudre watershed (zone 3) would be expected to have the largest magnitude flows in June (due to snowmelt), in the lower watershed and Buckhorn Creek (zone 1N) the largest floods are expected during the May through September (Figure 3, Yochum et al. 2019), due to rain events.

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Notices and Technical Tips

- **Direct technical assistance from applied scientists at the National Stream and Aquatic Ecology Center** is available to help Forest Service field practitioners with managing and restoring streams and riparian corridors. The technical expertise of the Center includes hydrology, fluvial geomorphology, riparian plant ecology, aquatic ecology, climatology, and engineering. If you would like to discuss a specific stream-related resource problem and (if needed) arrange a field visit, please contact a scientist at the Center or David Levinson, the NSAEC program manager.

- **Labor of Love to Restore Watershed Takes Collaboration**

  For two years, the Salmon-Challis National Forest staff worked with the Shoshone-Bannock Tribes to develop a watershed-based restoration plan from the headwaters to the mouth of Panther Creek, a tributary of the upper Salmon River in Idaho. The waters had become so polluted that the fish that Tribes in the area had relied on for generations were no longer available to sustain the Tribes.

  "It took a long time, but we finally have a plan that incorporates the Tribe's concerns," said Shoshone-Bannock Tribes Chairman Ladd Edmo. "We look forward to continued work with the Forest Service."

  The full Forest Service Tribal Relations blog post is available here.

- **Forgotten Legacies: Understanding Human Influences on Rivers**

  Logging, urbanization, and dam building are a few ways people have significantly altered natural river ecosystems. Understanding that influence is a grand challenge of our time.

  The EOS Earth and Space Science News article is available here.

WooDDAM: A Framework for Monitoring and Understanding Natural and Engineered Wood Jams

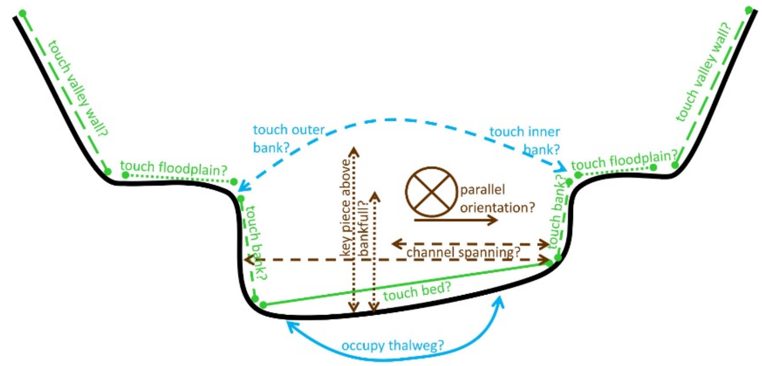

Figure 7: Illustration depicting wood jam geometry and location measurements, and how they each determine either where a wood jam is located within a channel cross-section or the relative dimensions of the jam. Blue depicts explicit location metrics. Green depicts channel boundary location metrics. Brown depicts wood jam geometry and orientation metrics. These measurements, in combination with the other measurements prescribed in the WooDDAM field protocol, provide a comprehensive description of the location, size, and orientation of a wood jam relative to the geometry of the channel.

Wood jams are fundamental components of forested river systems (Wohl et al., 2019). The Wood jam Dynamics Database and Assessment Model (WooDDAM) provides a framework for restoration practitioners and river researchers to monitor and understand how wood jams change in response to high flows. High flows can mobilize and alter the structure of wood jams (Kramer & Wohl, 2016), hampering monitoring and prediction of wood jam dynamics and the effort to balance wood jam ecological benefits (e.g., Coe et al., 2009; Francis et al., 2008) with potential risks to people and infrastructure (e.g., De Cicco et al., 2018). To overcome these difficulties, WooDDAM solicits data from multiple users who in turn benefit from a public database that lends context to understanding wood jams in a given region and forms the basis for statistical models that may be able to predict wood jam dynamics. Therefore, **we ask both practitioners and researchers to use WooDDAM and submit wood jam dynamics observations to the database** to increase the database size and it's predictive capabilities.

WooDDAM consists of three components (Scott et al., 2019). A reproducible field protocol uses primarily categorical observations to rapidly measure wood jam location, geometry (Figure 7), and physical characteristics, as well as channel geometry, reach-scale valley bottom characteristics, and hydrologic regime. These characteristics can be measured in a single wood jam survey (typically 5-15 minutes in the field with 1-2 people), which will enable a user to generate wood jam dynamics predictions for surveyed jams, as well as a repeat-photography-based resurvey to monitor wood jam dynamics through time. A public database archives these data, facilitates ancillary research (e.g., determinations of typical wood jam characteristics for a given region), and feeds machine learning predictive models of wood jam dynamics. These machine learning models are based on logistic regression and use wood jam characteristics to predict the probability of a wood jam mobilizing, accumulating wood, losing wood, expanding or contracting during flow that is below, near, or above bankfull stage.

The online user interface for these components provides instructions for collecting data, submitting data to the database, and using the machine learning models to obtain wood jam dynamics predictions. These models are currently in a development stage as new data is added to the database. We expect them to be robust enough for public use over the next 1-3 years, or sooner if more users submit data to the database.

We have implemented WooDDAM to monitor natural and engineered wood jams across the western United States, showing that the framework is widely applicable to diverse fluvial environments (Figure 8). As of October 2019, the database includes 511 unique wood jams, with 389 repeat surveys of wood jam dynamics over 19 rivers ranging in slope from 0.01 to 27.7% and bankfull width from 3.2 to 228 m. These data enable a preliminary model of wood jam mobilization that predicts that wood jams are less likely to mobilize during bankfull or higher flows when they include key pieces sourced from the banks (in situ) and when they reside in a multi-thread (as opposed to single-thread) channel planform. This preliminary model performs significantly better than random chance and correctly predicts mobilization approximately 25% of the time. For comparison, if guessing based on the rate of mobilizations observed in the database, one would guess correctly only 10% of the time. As users submit data to the database, we will update the predictive models to make them sufficiently robust for public use.

Figure 8: Jams currently in the WooDDAM database. A) An as-built wood jam on the South Fork McKenzie Stage 0 restoration project, Oregon. B) Daniel Scott surveying a large wood raft on the Hoh River, Washington. C) Ellen Daugherty surveying a small wood jam on the floodplain of the S. F. Poudre River, Colorado. D) An anchored engineered log jam on Hurst Creek, Washington.

While we continue to add wood jam dynamics observations, **we ask that others use WooDDAM and also submit wood jam dynamics observations to the database**. WooDDAM represents a hypothesis: that a community-led data gathering approach coupled with machine learning statistical techniques can develop our understanding of the complex processes that regulate wood jam dynamics. By helping to understand those processes, users can obtain context for their observations from the WooDDAM database and eventually obtain predictions of wood jam dynamics to aid in wood reintroduction and retention efforts. Please help us develop WooDDAM into a useful community data and prediction service by implementing WooDDAM to monitor both natural and engineered wood jams. Learn more here.

Acknowledgements

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